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A Numerical and Experimental Study of Steam Condenser Working with Modified Rankine Cycle

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ABSTRACT

A Numerical and experimental study of thermal and heat transfer processes in a steam condenser operating in steam power plant with steam engine was developed to built analytical model using to predict thermal profile of condenser. Iterative technique between Engineering Equations Solver (EES) and Matlab programming was developed to find water properties .The exit water temperature, steam flow rate, geometric dimension (diameter and tube length) ,convection heat transfer coefficient of water and condenser efficiency were computed using the analytic model. Experimental results for a range of water flow rate (0.0153 to 0.0121 kg/s) with constant inlet water temperature of 25 $^{\circ}C$ were used to validate the analytical model. Compared with a validated model, the standard deviations of analytical model are less than 4%, and all errors fall into ±6%. Analytical model can be used to show the relation between thermal parameters.

Keywords: Steam Condenser, Analytical Model, Engineering Equation Solver (EES), Unit Steam Power Plant.

دراسة عددية وعملية لمكثف بخاري يعمل بدورة رانكن المعدلة

الخلاصة

تضمن العمل في هذا البحث دراسة عددية وعملية لكل من عمليات داينميك وانتقال الحرارة لمكثف بخاري يعمل بوحدة توليد قدرة تستخدم محرك بخاري لبناء موديل رياضي يستخدم للتنبؤ بالأداء الحراري للمكثف . اعتمد على تقنية التكرار بين (EES) و(Matlab) بداءً من قيم الإدخال الأولي للحصول على خواص الماء. يستخدم الموديل الرياضي للحصول على درجة حرارة خروج الماء ومعدل تدفق البخار و قطر وطول الأنبوب ومعامل انتقال الحرارة بالحمل لماء التبريد مع كفاءة الأداء للمكثف. وحدة توليد قدرة تم اعتمادها للحصول على النتائج المختبرية ولمدى من قيم تدفق ماء التبريد (0.0153 - 0.0121 kg/s) ودرجة حرارة ثابتة لدخول الماء (25 $^{\circ}C$) لتصديق نتائج الموديل. عند مقارنة نتائج الموديل الرياضي مع النتائج المختبرية وجدنا

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انحـراف معيـاري اقـل مـن ٤% ونسـب خطـاء تقـع ضـمن حـدود ±٦%. يمكـن اسـتخدام الموديـل الرياضـي لبيان علاقة الخواص الحرارية فيما ببينها.

INTRODUCTION

A steam condenser has two main advantages: The primary advantage is to maintain a low pressure (atmosphere or below atmosphere pressure) so as to obtain the maximum possible energy from steam and thus to secure a high efficiency.
The secondary advantage is to supply pure feed water to the hot well, from where it is pumped back to the boiler. Steam engine with atmospheric condenser widely use in training and experimental devices.
Several investigators have proposed mathematical modeling with experimental work.

Valencia [1] performed a CED simulation for the condensation of water vapor based on empirical correlations using the Engineering Equation Solver (EES) were carried out for a two dimensional (2D) vertical water-cooled plate. The discrepancies between experiments and simulation are in a range of 7-25% depending on the combustion condition and the average surface temperature of the plate. Seungmin [2] A theoretical analysis on complete condensation in a vertical tube passive condenser was performed. The modified Nusselt model agrees well with the experimental data. The condensation rate increase and the condensation heat transfer coefficient decrease as the system pressure increases. Mohammed .Ameri [3] presents a method for the estimation of power plant thermal profile and shows the effect of key design parameters. The temperature profile of Shahid Rajaiee power plant in multi-zone model and it has been compared with the actual profile; it has been shown that it is 2.9%-3.74. Patcharin .Saechan [4] presents a mathematical model for determining optimal configuration of plate finned tube condensers. Results from the mathematical model show that entropy generation number decrease with increasing fin pitch and decreasing number of rows and tube diameter. Y. Haseli [5] present evolution of the optimum cooling water temperature during condensation of saturated water vapor within a condenser. The optimization problem is defined subject to condensation of the entire vapor mass flow. The optimization results are obtained at two different condensation temperatures of an industrial condenser. K.Medjaher [6] presented a simulation model for a vertical U-tube steam condenser; the storage of hydraulic and thermal energies is represented using a coupled pseudo-bond graph model. The simulation results obtained from the bond graph model are validated with experimental data from a laboratory set-up. Kwangkook Jeong, [7] present an analytical model of heat and mass transfer processes in a flue gas condensing heat exchanger system. A pilot-scale heat exchanger was used to validate the analytical model. The experimental results show a very good agreement with analytical model results.

Convert manual use of devices to control by computer it's very important today because it is allow to work with device and performance limits to be explored without risking and with minimize errors. The focus of this study is a built analytical model of steam condenser used a little data was available and substance empirical correlation of heat transfer in thermodynamic relation of steam and cooling water to find all other thermal parameters and geometric dimension (diameter and length of tube) of steam condenser based on Iterative technique between Engineering Equations Solver (EES) and Matlab programming to simulate actual case.

ANALYTICAL MODELING

A. Description of condenser

The steam (1) condenses in the condenser shown in figure (1) on a cooling coil (2). The amount of cooling water passing through the cooling coil is indicated via the variable-area flowmeter and adjusted using the needle valve.

The condensate (3) is stored at the bottom of the condenser and can be drawn off via the valve (V5).A measuring container enables the amount of steam to be determined. An overflow (4) prevents the complete flooding of the condenser and prevents the creation of over pressure.

B. Modeling assumption

To develop an intermediate complexity model, the following assumptions are made:

* The maximum film thickness is small when compared to the tube diameter.
* Steady state one dimensional flow.
* The condensate flow is laminar. [6]
* The cooling water flow is turbulent. [8]
* The logarithmic mean temperature difference $\Delta T_{\ln}$ is obtained by tracing the actual temperature profile of the fluid along the tube, and is an exact representation of the average temperature difference (decays exponentially in the flow direction) between the fluid and the surface.
* Heat transfer over/from the condensate (Water) at the bottom of the condenser is negligible.

C. Governing equations

The control volume used for deriving the governing equations is defined as a fixed region in space that encompasses the steam and cooling water tube. Figure (2) shows the variables in the control volume.

In steam condenser there is no change in kinetic and potential energies. Also there is no work done by the system.

Now consider steady one-dimensional heat flow through a tube wall as shown in figure (3) of surface area A and thermal conductivity k, that is exposed to convection on both sides to fluids at temperatures T_S and T_w with heat transfer coefficients h_w and h_s ,respectively. Heat transfer from maximum temperature T_s to lower T_w temperature.

The heat transfer based on the thermal resistance can be defining as follows:

$$Q = U.A.dT_{ln} \quad (1)$$

Where U is the overall heat transfer coefficient, taking into account resistance from the steam to the cooling water. These resistance expressed in terms of the associated heat transfer coefficients as shown below: [7]

$$\frac{1}{U.A_{out}} = \left[\frac{1}{h_W} + F_{in}\right]\frac{1}{A_{in}} + R_{wall} + \frac{1}{h_S.A_{out}} \quad (2)$$

The fouling factor (F_{in}) and the tube wall resistance are assumed to be negligible in this analysis, A_{in} are replaced by A_{out} (the heat transfer area based on the tube outer diameter). [6]

When the convection heat transfer coefficient is very large ($T_S \approx T_{wall_{out}}$), thus convection resistance becomes very small and approach to *zero*. [8]
Thermal resistance of tube material is negligible because the small value of thickness . [7] After this assumptions eq(1) can be written as follow .

$$\frac{1}{U.A_{out}} = \frac{1}{h_W.A_{out}} \quad ; U = h_W \quad \ldots(3)$$

From fig.(4) Note that the temperature difference between the fluid and the surface *decays exponentially* in the flow direction, to solve this problem we use logarithmic mean temperature difference. [9]

$$dT_{ln} = T_S - T_W = \frac{\Delta T_e - \Delta T_i}{ln\frac{\Delta T_e}{\Delta T_i}} = \frac{T_W)_i - T_W)_e}{ln\frac{T_S - T_W)_e}{T_S - T_W)_i}} \quad \ldots(4)$$

The Nusselt number relations uses in several references are fairly simple, but they may give errors as large as 25 percent. This error can be reduced considerably to less than 10 percent by using more complex but accurate relations such as. [10]

$$Nu = \frac{(f/8)(Re - 1000)Pr_W}{1 + 12.7(f/8)^{0.5}(Pr_W^{2/3} - 1)} \ldots(5)$$

For *smooth* tubes, the friction factor (*f*) can be determined from the explicit *first Petukhov equation*:[10]

$$f = (0.79\, ln\, Re - 1.64)^{-2} \quad \ldots(6)$$

From defined Nusselt Number we can write convection heat transfer coefficient as below:

$$h_W = \frac{Nu * k_W}{D} \quad \ldots(7) \quad (7)$$

The **Reynolds number,** which is a *dimensionless* quantity, and is expressed for flow in a circular tube as:

$$Re = \frac{\rho_w * V * D}{\mu_w} \quad \ldots(8)$$

Under steady conditions the rate of heat transferred from steam equal the rate of heat passing through thermal resistance as shown in eq(9):

$$m^{\bullet}s.(h_1 - h_2) = h_w.A.\frac{T_w)_i - T_w)_e}{ln\frac{T_s - T_w)_e}{T_s - T_w)_i}} \quad \ldots(9)$$

From Newton's law of cooling, the increase in the energy of the fluid (represented by an increase in its mean temperature by $dT_{\ln}$) is equal to the heat transferred to the fluid from the tube surface by convection. Taking the exponential of both sides and solving for *Te* gives the following relation which is very useful for the determination of the *mean fluid temperature at the tube exit:* [10]

$$T_w)_e = T_S - (T_S - T_w)_i)\, e^{\frac{-h_w.A}{m^{\bullet}w.cp_w}} \quad \ldots(10)$$

Condenser efficiency necessary to understand thermal working, based on fig. (4) We can write efficiency as shown below: [11]

$$\eta = \frac{\Delta T_w}{\Delta T_i} \quad \ldots(11)$$

Substitute equs. (5, 6, 7, 8, 10) between them and simplifing the result gives exit water temperature as function of the water flow rate and tube diameter based on empirical correlation of heat transfer .

NUMERICAL SCHEME

The inlet water temperature was used as a target value and served as the criterion for convergence. Initially properties of water (μ_w, cp_w, k_w, Pr_w) calculated from (EES) [12] .Value for the exit water temperature was initially assumed, and the calculation were carried out. The scheme iterated until the correct inlet water temperature was calculated. The known variables (water flow rate, range of diameter and tube length from available marketing standard) with governing equations were solved using an iterative scheme to find water properties based on average water temperature , steam flow rate , geometric dimension (diameter and length of tube) ,convection heat transfer coefficient of water and condenser efficiency .

EXPERIMENTAL

The experimental study was carried out to validate the analytical model. Figure. (5) Show the overall experimental set up of unit Steam power plant. The experimental setup consisted of feed water tank, feed pump, and gas-heated boiler, piston steam engine with generator, condenser and safety equipment. [13, 14]

Function Schematic Diagram as shown in Fig. (6) Show Measurements, valves and Safety Equipment using in experimental work .The feed pump draws the water from the feed water tank and drives it through the non-return valve (V2) into the boiler. The water level is checked using a water level gauge (L1).A manometer (P1) indicates the steam pressure in the boiler. The steam pressure is measured using (T3).A safety valve (V3) prevents excessively high pressure. The steam enters the steam engine via shut-off valve (V4). The steam inlet temperature is measured at (T4), the steam outlet temperature at (T5), the waste steam from the engine is fed to the condenser. The condensate can be drained from time to time using valve (V5) and collected in a measuring container. The condensate temperature is measured using (T6). The cooling water for the condenser flows from the water connection through the regulator valve (V6) and flow meter (F1) to the condenser. From there it flows to the drain. Inlet temperature and outlet temperature of the cooling water are measured using (T7) and (T8).

Operation the power plant start from starting the boiler and when the pressure is greater than (0.8 bar) ,the steam engine can be placed in operation by opened steam valve a little and start the steam engine by rotating the flywheel. The load can be adjusted by switching on the light bulbs and the speed is adjusted using the steam valve. Adjusted cooling water for condenser using regulator valve And Condensate can be drained off via (V5). The determination of the amount of steam is performed via measurement of the condensate using a measuring plastic container. [15]

When the system has reached to a steady state can be read some measurements: temperature of outlet Steam engine, condensate temperature, cooling water inlet and outlet temperature, cooling water flow rate, amount of steam condensate and period of time using watch to calculate steam flow rate based on following equation:

$$m^{\bullet}s = \frac{\rho_W * V_W}{\Delta t} \qquad \ldots(12)$$

After a few minutes the pressure of boiler is adjusted using the steam valve and repeat reading more than ones for the same measuring points.

RESULTS AND DISCUSION

The results such as comparison between the analytical module and experimental work data, the effect of parameters on the thermal profile of steam condenser are presented.

Analytical modeling for steam condenser was performed using the experimental test conditions, five output variables are results from analytical modeling: exit water temperature, convection heat transfer coefficient of cooling water, mass flow rate of steam, efficiency and chose correct value of diameter and tube length. Experimental data selected to verify the analytical model were conducted with same inlet conditions.

Figures (7) to (9) show the variations of the predicted and measured exit water temperature. The x-axis represents the steam temperatures enter to the condenser. The condenser operating conditions for the tests are listed in the figure. Predicted and measured data are shown increase exit water temperature with increase steam temperature and it is decrease with increase mass flow rate of cooling water.

Figures (10) to (12) shows the variations of the predicted and measured steam mass flow rate. The x-axis represents the steam temperatures enter to the condenser .For this particular test condition in figures (10) to (12) inlet cooling water temperature was $25^\circ C$. Predicted and measured data show an increase in steam flow rate with increase steam temperature and increase mass flow rate of cooling water.

Figure (9) to (12) show the deviation range ±5%, which is considered an acceptable minimal deviation [7] ٠As can be seen from these figures, there is good agreement between the experimental and the predicated values of both exit water temperature and steam flow rate. acceptable value of deviation results come from calculate exit water temperature based on empirical correlation, Water properties evaluated as function of average water temperature and iterative between EES and Matlab programming. These results show that the theoretical model used in this paper can predicate the heat transfer in the condenser with good accuracy.

Figure (13) to (14) show the variations of the predicted and measured geometric dimension (diameter and tube length). The x-axis represents the steam temperatures enter to the condenser. The average uncertainties of the measured and measured geometric dimension (diameter and tube length) were ±6%. The results showed that the analytical model can accurately predict the diameter and tube length of condenser.

Figure (15, 16, and 17) show the effects of steam and exit water temperatures on the convection heat transfer coefficient of water. The results show increase convection heat transfer coefficient of water with increase exit water temperature and decrease steam temperature because increase heat transfer for the same value of inlet water temperature and mass flow rate of water . It is also show the value of convection heat transfer coefficient of water increase from figure (15) to figure (16) and (17) because increase mass flow rate of water (see Eq. (4,5,6,7)). Also shown in three figures (15, 16, and 17) more highest values (not acceptable) of convection heat transfer coefficient of water with steam temperature little than 70 $W/m^2.^\circ C$ And exit water temperature greater than $40^\circ C$ because higher quantity of heat transfer with small mass of cooling water.

Figure (18, 19, and 20) shows the effects of steam and exit water temperatures on the steam mass flow rate. The results show increase steam mass flow rate with increase exit water temperature and steam temperature because increase heat transfer from steam to the cooling water for the same value of inlet water temperature and mass flow rate of water. It is also show the value of steam mass flow rate increase from figure(18) to figures (19) and (20) because increase mass flow rate of water (see Eq. (8,9)). Also shown in three figures (18,19,20) more highest values of steam mass flow rate with steam temperature greater than $75^{\circ}C$ and exit water temperature greater than $40^{\circ}C$ and steam mass flow rate depended strongly on exit water temperature more than steam temperature because higher quantity of heat transfer happened on the bigger different in water temperature.

Figure (21) Show the effect of steam temperature and exit water temperature on the condenser efficiency. The results show increase efficiency with increase exit water temperature and decrease steam temperature because approach exit water temperature from steam temperature help to transfer bigger quantity of heat from steam to cooling water and improve condenser working.

Table (1) show a comparison between two ways of calculated coefficient of convection by use analytical model and heat balance between thermal resistance and cooling water based on experimental operational conditions. The small values of errors prove the accuracy of mathematical model and prove of eq.(3) .

CONCLUSIONS

An analytical model of steam condenser was developed using connected between fundamental heat transfer and thermodynamics relation, thus exit water temperature as a function of the water flow rate and tube diameter. Determine water properties and other thermal parameters based on average water temperature by solving all governing equations using an iterative technique between EES and Matlab program.

Experimental were carried out to validate the analytical model. Measurements were made and experimental results were compared to the results from theoretical model.

Mathematical model use to determine diameter and tube length from available range based on amount of heat transfer and inlet water temperature served as the criterion for convergence.

The results from analytical modeling, using the same operational conditions as the experiments, agreed well with experimental results. The exit water temperature, steam mass flow rate, diameter and length of tube were used to compare the tests. The average discrepancy between the results of the analytical model and experiments were within a few percent. These results show that the theoretical model used in this paper can predicate the heat transfer in the condenser with good accuracy .Analytical model used to show the effects of steam and exit water temperatures on the convection heat transfer of water , steam mass flow rate and efficiency.

Model variables (Nomenclature)

Variable	Description	
A	Surface area	m^2
cp	Specific heat	$kJ/kg.^\circ C$
D	Diameter	m
dT	Differential Temperature	$^\circ C$
dh	Differential enthalpy	kJ/kg
f	Friction factor	
F_{in}	Fouling factor	
h	Convection heat transfer coefficient	$W/m^2.^\circ C$
h_1	Inlet steam Enthalpy	kJ/kg
h_2	Exit steam Enthalpy	kJ/kg
k_w	Thermal conductivity of water	$W/m.^\circ C$
L	length of tube	m
$m^\bullet$	Mass flow rate	kg/s
NU	Nusselt Number	
P	Steam Pressure	bar
P_r	Prandtl number	
Q	Heat transfer	$watt$
r	Radius	m
Re	Reynolds number	
R	Resistance	
R_{wall}	Wall resistance	$m^2.^\circ C/W$
t	Time	S
T	Temperature	$^\circ C$
T_w	Water temperature	$^\circ C$
T_{wall}	Wall temperature	$^\circ C$
U	Overall heat transfer coefficient	$W/m^2.^\circ C$
V	Velocity	m/s
V_w	Volume of condensate	m^3
V_5	valve	
X	Dryness friction	

Greek symbols

Variable	Description
Δ	difference

Subscripts

Variable	Description
e	exit
i	inlet
in	inner
ln	logarithmic
out	outer
s	steam
w	water

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Table (1) compare between two ways of calculated coefficient of convection

$T_w)_{average}$ From experimental work	k_w from EES	Pr_w from EES	cp_w from EES	μ_w from EES	T_S From experimental work	$m^\bullet_w$ From experimental work	h_w use mathematical model	h_w heat balance	Absolute Error
29.5	.6022	5.601	4.183	.00081	70	.0153	1584.9	1568.2	1.1%
31.5	.6053	5.341	4.183	.00077	88	.0153	1682.3	1652.6	1.8%
32.5	.6053	5.341	4.183	.00077	87	.021	2351.1	2381.9	1.3%
33.5	.6084	5.099	4.183	.00074	104	.021	2457.9	2421	1.5%

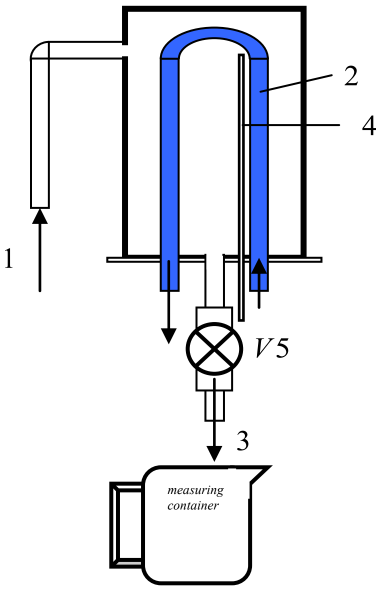


Figure (1) Atmospheric Condenser Us in experimental work.

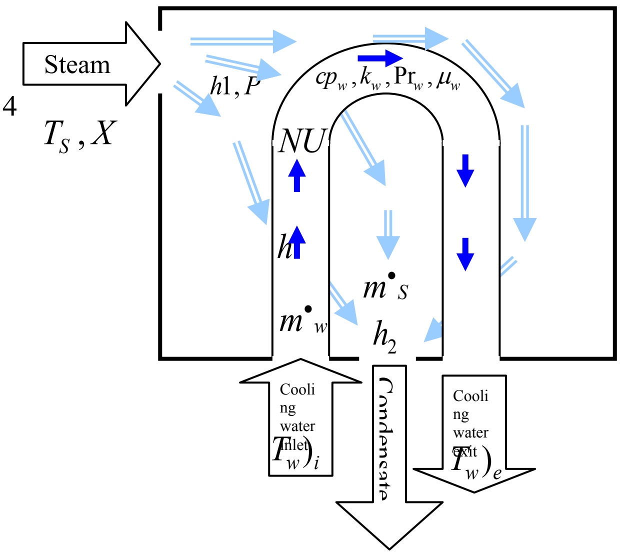


Figure (2) Control volume and variablesFor mathematical modeling.

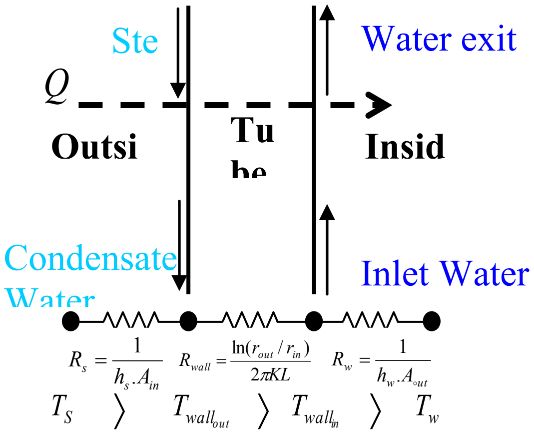


Figure (3) Thermal resistance from steam Side to cooling water side.

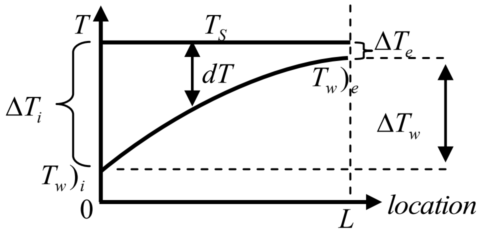


Figure (4) the variation of mean fluid temperature along the tube.

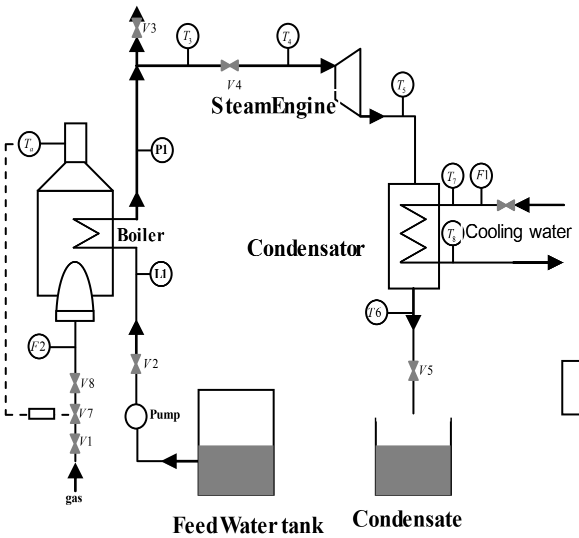


Figure (6) Function Schematic Diagram.

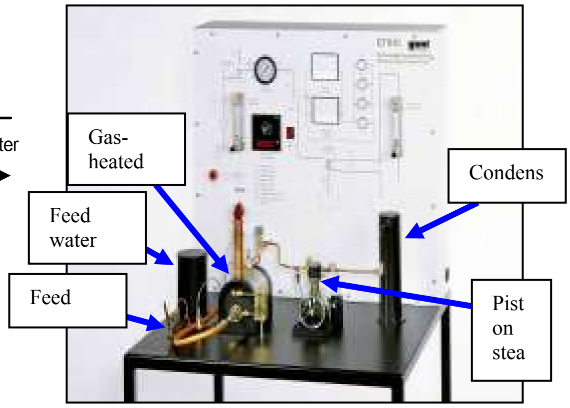


Figure (5) Single cylinder steam engine from G.U.N.T. comp.

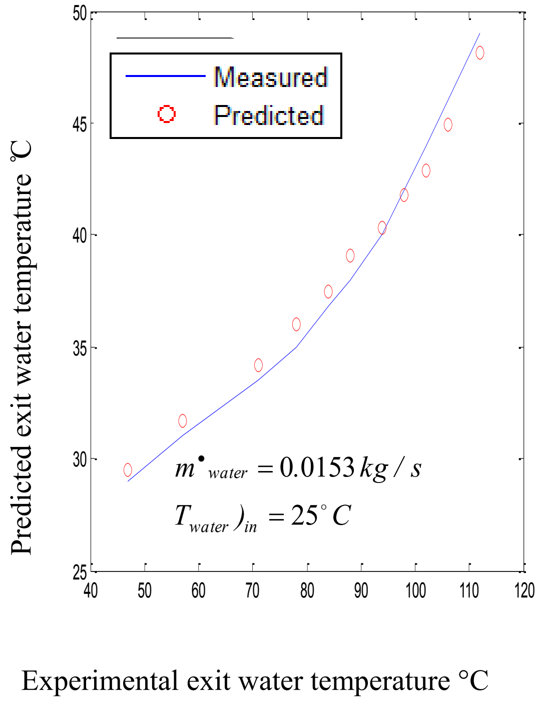
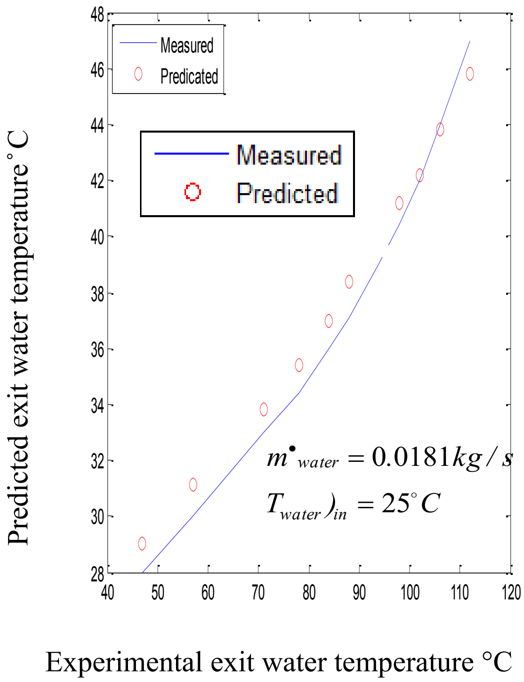


Figure (7) Deviation between the predicted exit water temperature and the experimental results.



Figure(8) Deviation between the predicted exit water temperature and the experimental results.

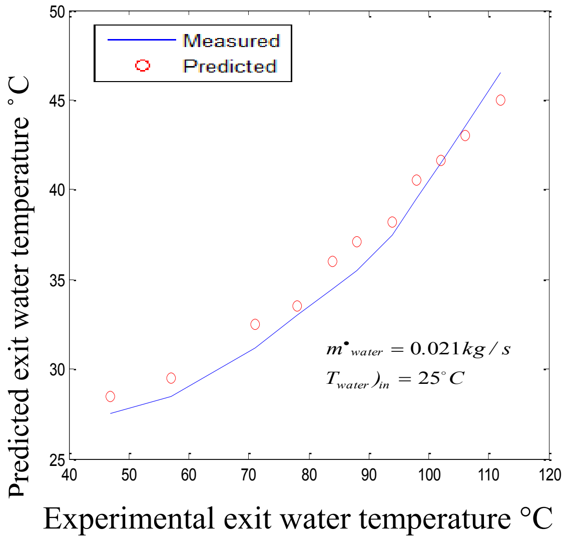


Figure (9) Deviation between the Predicted exit water temperature and the experimental results.

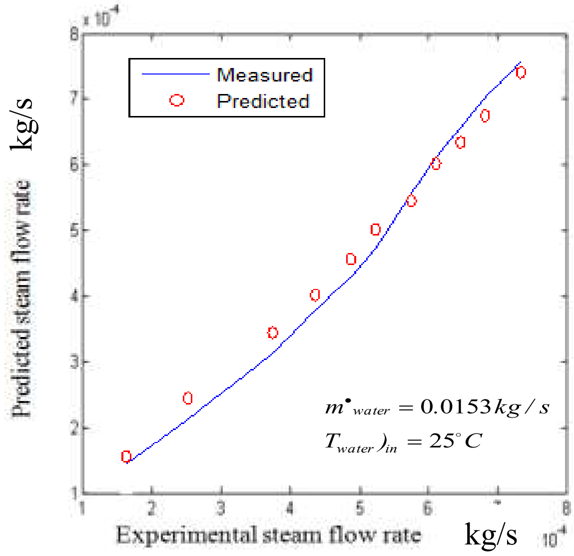
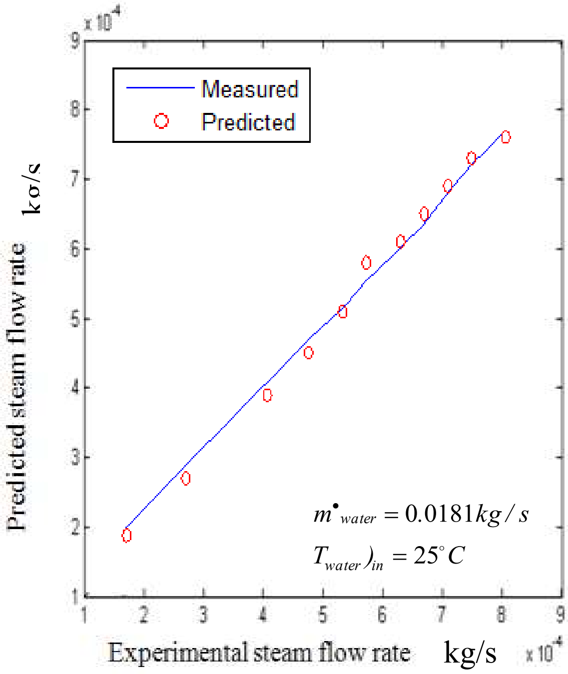


Figure (10) Deviation between the Predicted steam mass flow rate and the experimental results.



Figure(11) Deviation between the predicted Steam mass flow rate and the experimental results.

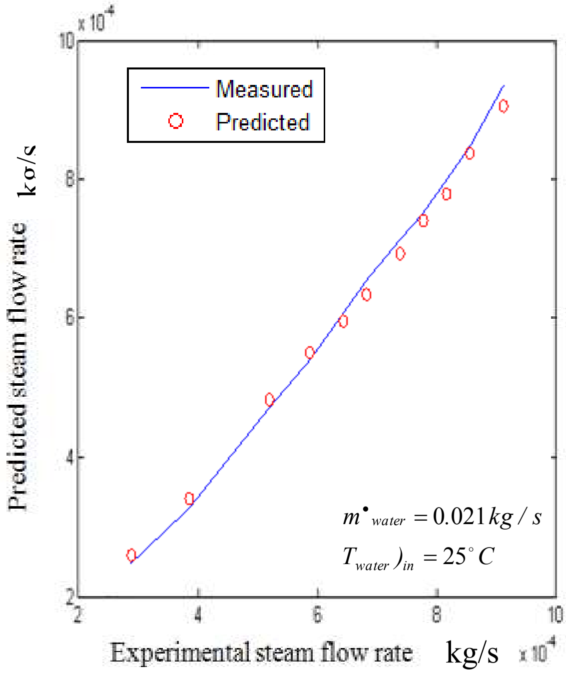
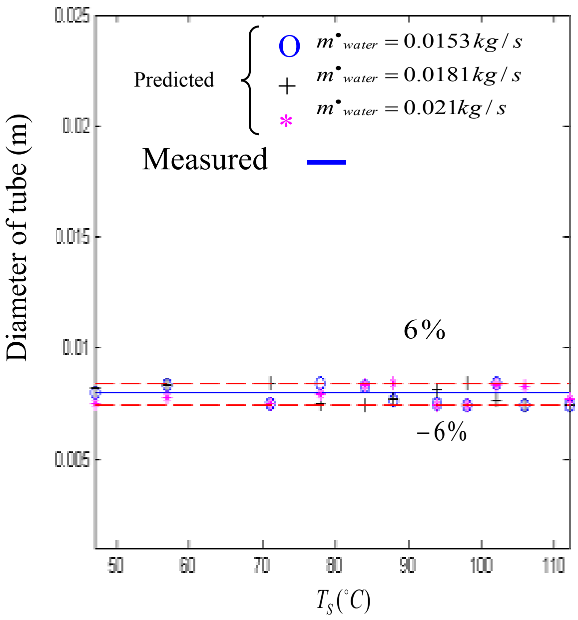
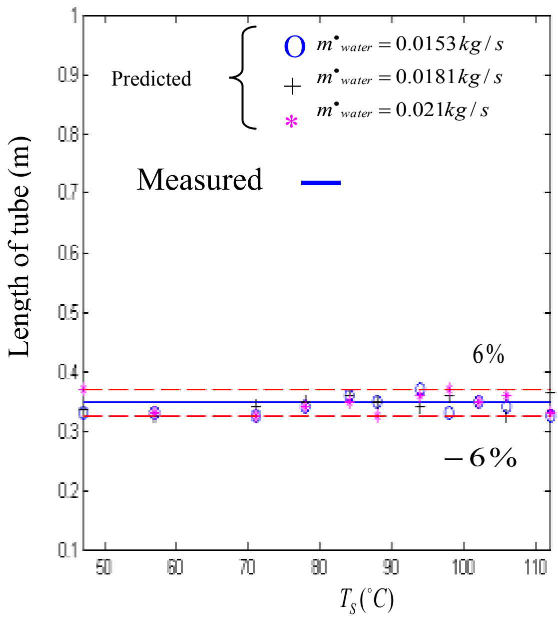


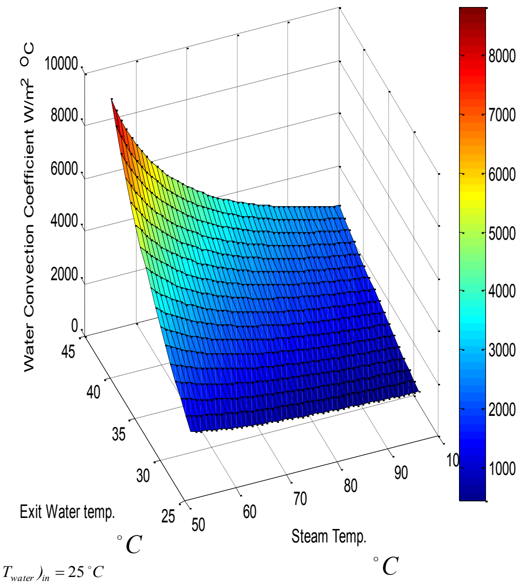
Figure (12) Deviation between the predicted steammass flow rate and the experimental results.



Figure(13) Deviation between the predicted Diameter of tube of condenser and the experimental results vs. steam temperature.

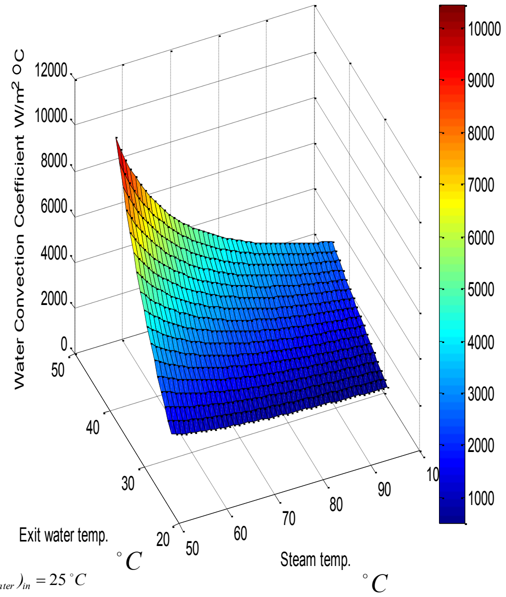


Figure(14) Deviation between the predicted lengthof tube of condenser and the experimental results vs. steam temperature.



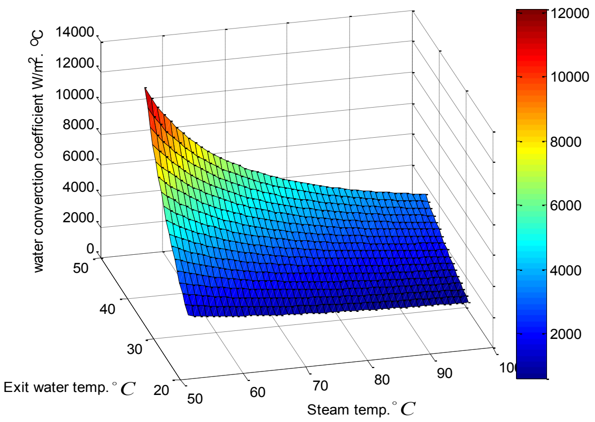
$T_{water})_{in} = 25\,^{\circ}C$
$A = 0.008\,m^2$
$m^{\bullet}_{water} = 0.0153\,kg/s$

Figure(15)The effect of the exit cooling water and steam temperatures on convection heat transfer coefficient of water.

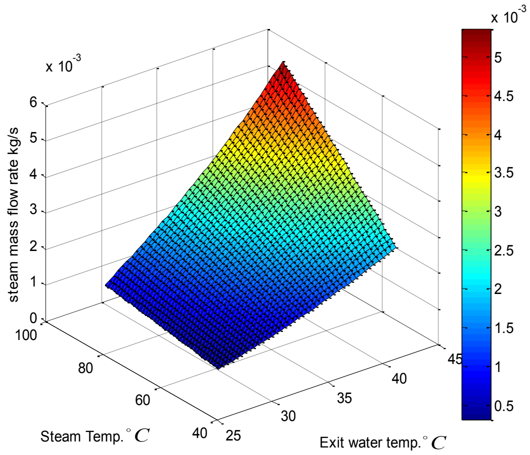


$T_{water})_{in} = 25\,^{\circ}C$
$A = 0.008\,m^2$
$m^{\bullet}_{water} = 0.0181\,kg/s$

Figure(16)The effect of the exit cooling water and steam temperatures on convection heat transfercoefficient of water.



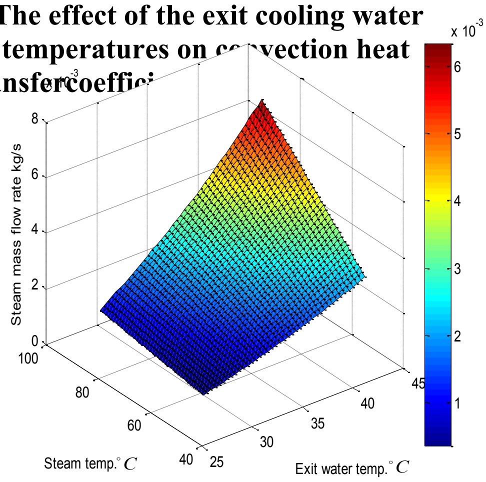
$T_{water})_{in} = 25\,^{\circ}C$
$A = 0.008\,m^2$
$m^{\bullet}_{water} = 0.021\,kg/s$

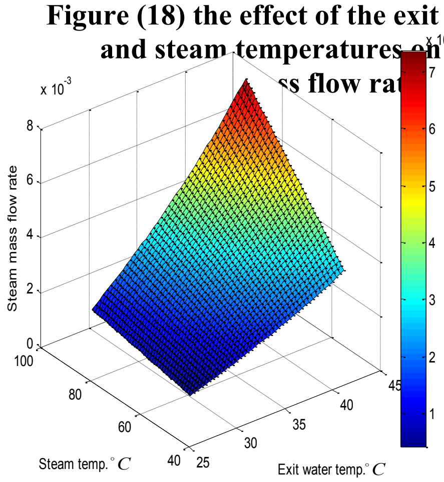


$T_{water})_{in} = 25\,^{\circ}C$
$A = 0.008\,m^2$
$m^{\bullet}_{water} = 0.0153\,kg/s$

Figure (17)The effect of the exit cooling water and steam temperatures on c vection heat transfercoeffi

Figure (18) the effect of the exit cooling water and steam temperatures n the steam ss flow rat





$T_{water})_{in} = 25^{\circ}C$

$A = 0.008 m^2$

$m^{\bullet}{}_{water} = 0.0181 kg/s$

$T_{water})_{in} = 25^{\circ}C$

$A = 0.008 m^2$

$m^{\bullet}{}_{water} = 0.0181 kg/s$

Figure (19) The effect of the exit cooling water and steam temperatures on the steam mass flow rate.

Figure (20) The effect of the exit cooling water and steam temperatures on the steam mass flow rate.

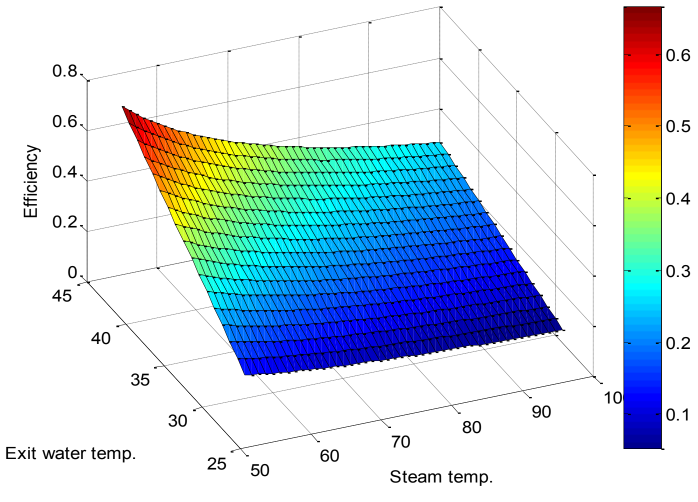


Figure (21) the effect of steam temperature and exit water temperature on the condenser efficiency.